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FRICTION OF THIN FILMS OF RUBBER-LIKE MATERIAL

James Byron Brook

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FRICTION OF THIN FILMS OF
RUBBER-LIKE MATERIAL

James Byron Brook

Friction of Thin Films of Rubber-Like Material

by

James Byron Brock, Lieutenant, U. S. Coast Guard
B. S., United States Coast Guard Academy, 1948

Submitted in partial fulfillment of the requirements
for the degree of Naval Engineer

at the

Massachusetts Institute of Technology

May 24, 1954

Friction of Thin Films of Rubber-Like Materials

by

James B. Brook, Lieutenant, U. S. Coast Guard

Submitted to the Department of Naval Architecture and Marine Engineering on May 24, 1954, in partial fulfillment of the requirements for the degree of Naval Engineer.

What is seen as a smooth surface is, on the microscopic level, rough and irregular. Two contacting surfaces are in contact only at the peaks of their surface asperities. The friction force between the two surfaces is thought of as that force arising from the shear strength of the randomly located islands of contact. It is seen that if a thin film of a soft material is deposited on a hard substrate, the friction force will be small.

In this investigation a thin film of neoprene was deposited on an annulus machined on one face of an aluminum disk. This annulus was then pressed against a roughened glass surface and rotated concentrically in a plane parallel to the glass. Rotation was accomplished by applying a tangential weight to the disk which was subjected to a fixed normal load. The speed of rotation was varied by varying the tangential load, and the friction test was carried out in an atmosphere of dry air, the temperature of which could be varied. The coefficient of friction was calculated from the definition

$$\mu = \frac{F}{W}$$

where

F = tangential load
W = normal load.

From this data curves of the logarithm of velocity against coefficient of friction for constant temperatures were plotted. This led to cross curves of ln V against temperature.

On the basis of the experimental curves it is proposed that the steady relative motion between the two surfaces can be approximated by the Boltzmann-Einstein equation. As the neoprene moves over the glass surface, the islands of the neoprene tend to remain in contact with the glass. This causes a local shear stress to be set up in the neoprene in the vicinity of each island. When the shear stress reaches a particular value the island breaks contact with the glass and assumes an unstressed position. The sum of all the randomly located slips results in the steady motion of the neoprene over the glass.

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The value of the shear stress which causes local slip is made of two components—the thermal activation of the molecules of the substance and the applied tangential load. From the curves this is seen in that both load and temperature influence the velocity of sliding. The curves further suggest that there are two bond strengths of the neoprene, one of which is far stronger than the other. The action of both bond strengths causes the curve of ln V vs μ at constant temperature to be parabolic in shape, while the action of the strong bonds alone gives the curve a linear shape.

Thesis Supervisor: Brandon G. Rightmire

Title: Associate Professor of
Mechanical Engineering

The value of the shear stress which causes local slip is made of two components—the thermal activation of the molecules of the substance and the applied tangential load. From the curves this is seen in that both load and temperature influences the velocity of sliding. The curves further suggest that there are two bond strengths of the lubricant, one of which is far stronger than the other. The action of both bond strengths causes the curve of ln V vs p at constant temperature to be parabolic in shape, while the action of the moving bonds alone gives the curve a linear shape.

Thesis Supervisor: Brandon G. Rightmire

Title: Associate Professor of
Mechanical Engineering

Cambridge, Massachusetts
May 24, 1954

Professor L. F. Hamilton
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Sir:

In accordance with the requirements for the degree of Naval Engineer I submit herewith a thesis entitled "Friction of Thin Films of Rubber-Like Material."

Respectfully,

ACKNOWLEDGEMENTS

The author wishes to thank Professor B. G. Rightmire for his assistance and encouragement in the preparation of this paper, and Mr. Owen F. Hedden, Research Assistant, for his valuable aid in obtaining experimental data and interpretation.

The author also wishes to express his grateful appreciation to his wife who contributed both moral and material aid during the entire preparation of this thesis.

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INTRODUCTION

At present, we picture two surfaces in contact with each other as being in contact at randomly located peaks. What we see macroscopically as smooth surfaces are, microscopically, irregular hill and valley terrain, with contact between the surfaces taking place at the peaks. We have visualized the friction force as being that force coming from the shear strength of minute local welds at the random points of contact. We then have the relation that

$$F = \gamma \times s, \tag{1}$$

where F is the friction force, γ is the average shear stress of the welds, and s is the total area of contact.[2] To keep the friction force as small as possible, it is obvious that γ and s must be small. If we choose a material of low shear stress, it is usually soft, so that although γ will be small, s will be large. If we choose a hard material, s will be small but γ will be large. However, if we deposit a thin film of a soft material on a hard substrate, the shear stress involved in the contact will be that of the soft material, while the normal load will be borne by the substrate. In this manner, the friction force will be small.[1] This permits us to investigate the surface effects of friction to the exclusion of forces plastically deforming the subsurface layers of the sliding bodies.

The frictional forces of thin films of soft metals—lead, indium, copper—have been investigated by Bowden and Tabor,[2] but in the case of dry sliding of metal on metal there is a transfer of metal at the interface and formation of loose wear particles. Local plastic deformation of either or both of the surfaces extends to a depth which is great in comparison to molecular dimensions. By using a highly elastic material—such as rubber—

as one of the surfaces we have a much simpler situation. Most of the irreversible effects of sliding contact then occur at the interface. We have investigated the mechanism of sliding friction of a thin film of neoprene on a glass surface at several different temperatures of the environment in an attempt to learn something of the nature of sliding friction itself. Rubber friction has been investigated by Schallamach [8] as to velocity and temperature dependence in a similar manner but with equipment of larger scale than ours.

PROCEDURE

In our equipment, a thin film of neoprene is pressed against a glass plate and rotated concentrically about an axis normal to the plane of contact. The neoprene was deposited on an annulus machined on one face of an aluminum disk. The annulus has a mean diameter of 0.890 inches, and is 1/8 inch in radial breadth. The disk and annulus are coated with Z-19-K* neoprene which was oven cured for two hours at 180°F (See Figures X; XII). The resulting film is of the order of 0.005 inches thick. The disk is placed on top of the flat glass test surface which is clamped rigidly to the test frame, and the neoprene is dressed lightly to produce a uniform surface. The apparent area of contact at the interface is 1.07 cm^2.

The normal load and the tangential load—the latter supplying the driving torque—are both applied to the disk through a vertical shaft and flexible connection. The end of the shaft is pointed and rests in a conical depression in the upper face of the disk so as to have point application of the normal load as nearly as possible. Three radial arms extend from the shaft end and contact vertical pins in the upper face of the disk. In this manner the driving force is transmitted from the shaft to the disk.

The shaft extends vertically upward through needle bearings mounted in a heavy steel block, and at the upper end of the shaft is rigidly attached a drum which supports the normal load (See Figures IX; XI). Two light cords are wrapped around the drum and run off horizontally in opposite

---

* Supplied by General Latex and Chemical Company, Cambridge, Massachusetts

directions. The cords pass over pulleys, and simple weight hangers at the end of each cord carry the variable tangential loads. By applying the load in this manner, bending of the vertical shaft is reduced as much as possible. On the upper face of the drum are scribed radial lines at intervals of 30°. These index lines permit observations of velocity of the rotating assembly to be made over any twelfth or multiple of a twelfth revolution. The disk, drum, and shaft are fixed relative to each other.

The glass surface has been roughened slightly with metallographic polishing paper of grade 1, since this condition led to the most reproducible results. The flexible connection between the disk and shaft permits the neoprene ring to press as uniformly as possible against the glass.

The test block can be enclosed so that the friction test can be carried out in any desired gaseous atmosphere. To bring the temperature of the incoming gas into equilibrium with that of the controlled temperature box, the gas passes through a two-foot run of copper tubing in the box before going into the block. This, when coupled with the low flow rate of the gas, allows us to say that the temperature of the gas in the immediate vicinity of the rotating disk is very close to that within the box itself. The weights used for the normal loads have been machined out of brass in the form of rings, so that the radial lines of the drum upper face can be viewed with the weights in place. The entire test block is mounted rigidly to the stage of a low power microscope, and with an ocular micrometer in the eyepiece, the velocity of the rotating parts can be computed from the timing of the passage of any two scribe marks.

The microscope assembly has been leveled and mounted in a temperature-controlled box, (see Figures VII;VIII), all of this being located in an air-conditioned, vibration-free room. It has been found that atmosphere and spurious vibrations have definite influences on the tests. The temperature of the air inside the box is measured with an ordinary laboratory mercury-type thermometer.

All tests have been run with one neoprene-coated ring in an atmosphere of dry air with a normal load of 365 grams. The temperature was varied from 22°C to 50°C (72°F to 122°F), and the tangential load varied from 170 grams to 510 grams. This implies a range of coefficient of friction u from 0.502 to 1.505; μ being calculated from the definition

$$\mu = \frac{F}{W}, \tag{2}$$

where F is the tangential load applied to the annulus and W is the normal load. To obtain the tangential force acting on the annulus, the tangential force applied to the drum is multiplied by the ratio of the diameter of the annulus to that of the drum. The velocity is calculated from the measurement of the time interval between the passage of two scribe marks across the index of the ocular micrometer.

The dimensions of the drum and the height of the apparatus dictate the amount of rotation possible without having to reset the equipment. We are able to get about three and one-half revolutions of the annulus for full travel of the weight hangers. After each run, the disk is removed from the test stand and is allowed to remain in the same environment, unstressed and unloaded, for several minutes. After each day's observations, the annulus

has been liberally rinsed in acetone and permitted to dry overnight. By following these foregoing steps we have been able to obtain reproducible results.

DISCUSSION OF DATA OBTAINED

From the data of this investigation—obtained by methods previously described—we were able to calculate the rotational velocity of the annulus. It was noted that the velocity was not uniform over one rotation of the disk but varied cyclically. Figure I illustrates this for a typical run. The radial coordinate is time—the number of seconds required for the disk to pass from the previous sector line to the one on which the time is indicated. In other words, the radial coordinate is a measure of the time for the disk to pass through 30° of rotation with a given tangential load and normal load applied to the annulus and a constant temperature of the environment. The straight lines joining the points have no significance other than to give continuity to a succession of individual values of time so that the fluctuations may be more readily apparent. It is seen that the velocity quickly reached a steady value after the beginning of the observation. Over the rotation of the disk there is a "flat spot" in the plot in the vicinity of sector 2, indicating a region in which the velocity exceeded the average. This flat spot occured over many runs at the same point, regardless of where the disk was started. It was found to change its location, however, when the test block was reoriented on the microscope stage. The red circle drawn on the plot represents the average time of 30° of rotation for the entire observation. We attempted to have about three revolutions of the disk in each observation, and the velocity was determined from the average time of rotation.

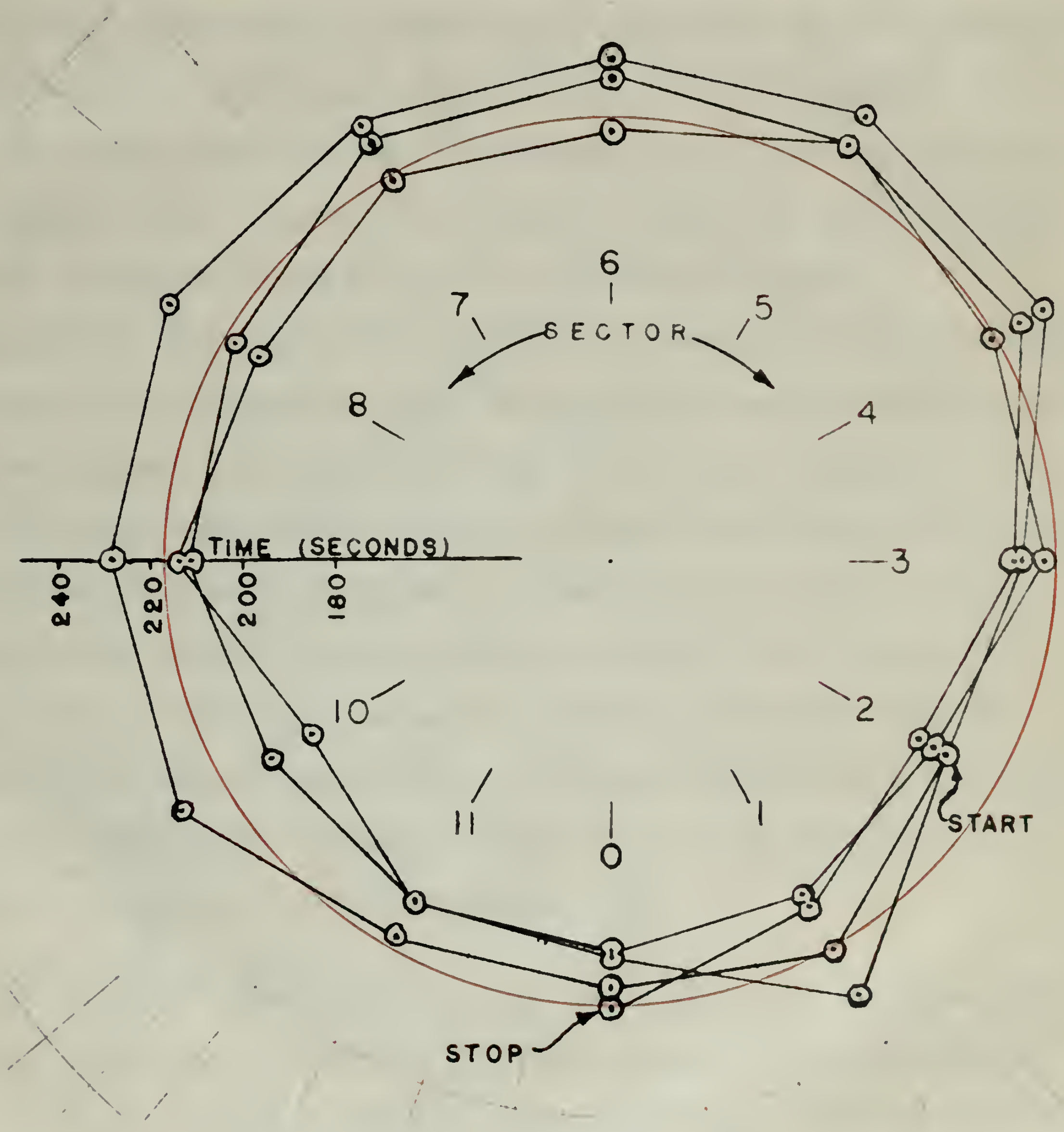
We were able to vary the temperature of the environment from $22^\circ C$ to $50^\circ C$ and Figures II, III, and IV show the results of the observations plotted as the logarithm of the average velocity against the coefficient of friction,

FIGURE. I

POLAR PLOT OF TIME FOR EVERY 30° OF ROTATION OF ANNULUS FOR TYPICAL OBSERVATION

NEOPRENE ON ROUGHENED GLASS
NORMAL LOAD = 365 GM

TANGENTIAL LOAD = 230 GM
μ = 0.68
TEMPERATURE = 22° C



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for constant temperatures. Each point represents the average of one full observation. It is to be remembered that the tangential force acting on the ring is adjusted for the difference in mean diameters of the ring and the drum. Only one normal loading was used—365 gm. It is seen from Figures II and III that for the low values of μ, the curve is concave downward—the velocity falls off rapidly as μ is decreased. However, for the higher values of μ, the logarithm of the velocity can be said to be, in the first approximation, linear with μ. There is some suggestion of downward concavity in this region of the curve, and this has been noted by Schallamach [8], but it is not clear at this time what the curvature should be; hence, the approximate straight line. Figure V is a composite plot of the curves of Figures II, III, and IV, and it can be seen that the curves of ln V vs. μ for temperatures in the range of 22°C to 40°C are approximately parallel throughout the scope of our observations. When the temperature exceeded 40°C we noted irregular response of the equipment—this is to be seen in Figure IV. In this temperature range it was difficult to obtain reproducible data because no steady velocity could be reached. A straight line is used as a rough estimate of the trend of the meager data we gathered in this range. This irregularity of the neoprene seems to be entirely reversible. When the temperature was lowered below 40°C, the equipment performed as it did previously. No change in the nature or behavior of the neoprene was discernible as a result of operations at a temperature above 40°C.

All observations have been made with the annulus in an atmosphere of dry air. The air, under a pressure of about 2 mm of Hg over atmospheric pressure, is led through a controlled temperature box and into the test block

FIGURE II

PLOT OF LOG VELOCITY AGAINST COEFFICIENT OF FRICTION AT CONSTANT TEMPERATURE

NEOPRENE ON ROUGHENED GLASS
NORMAL LOAD = 365 GM

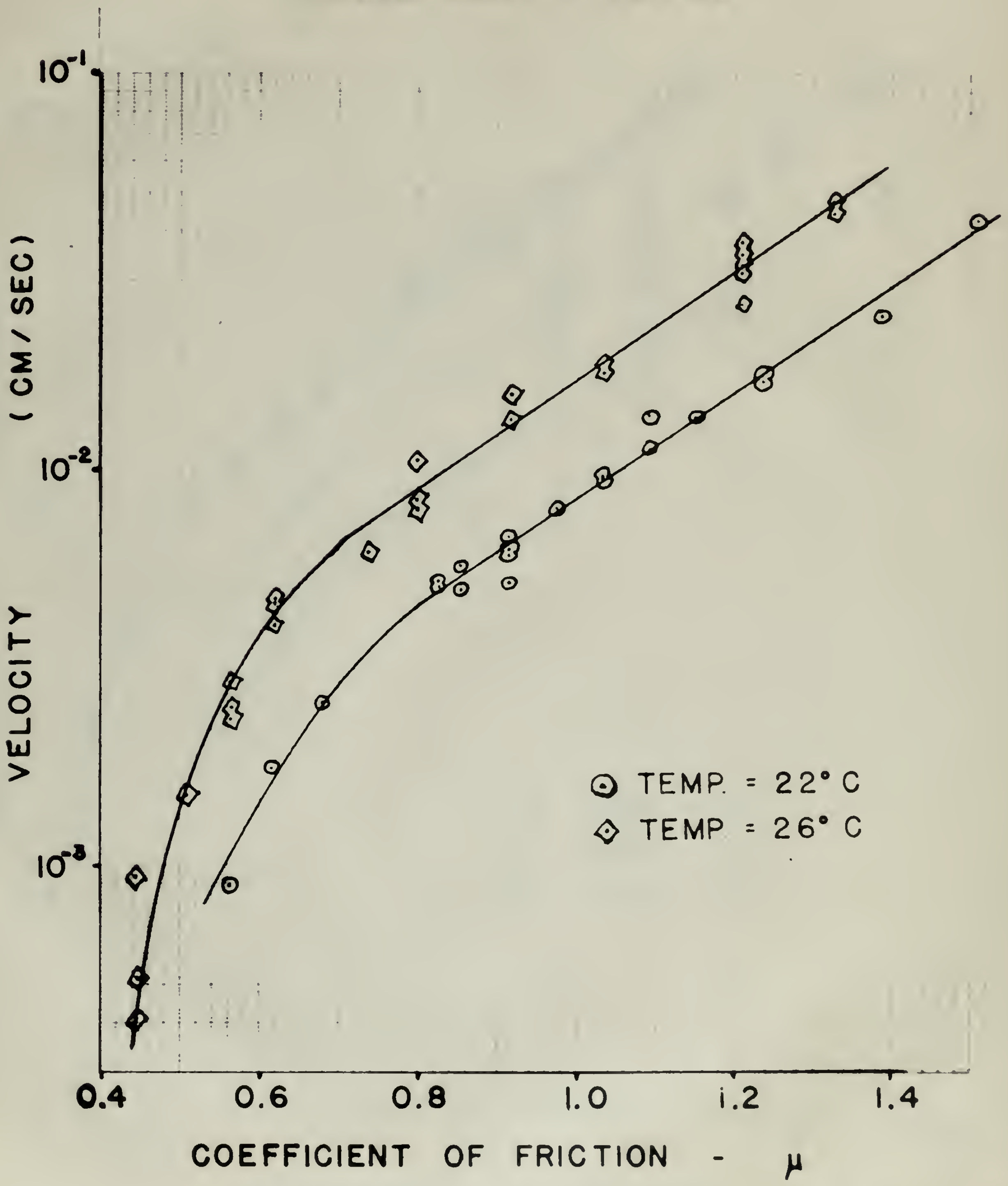

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FIGURE III

PLOT OF LOG VELOCITY AGAINST COEFFICIENT OF FRICTION AT CONSTANT TEMPERATURE

NEOPRENE ON ROUGHENED GLASS
NORMAL LOAD = 365 GM

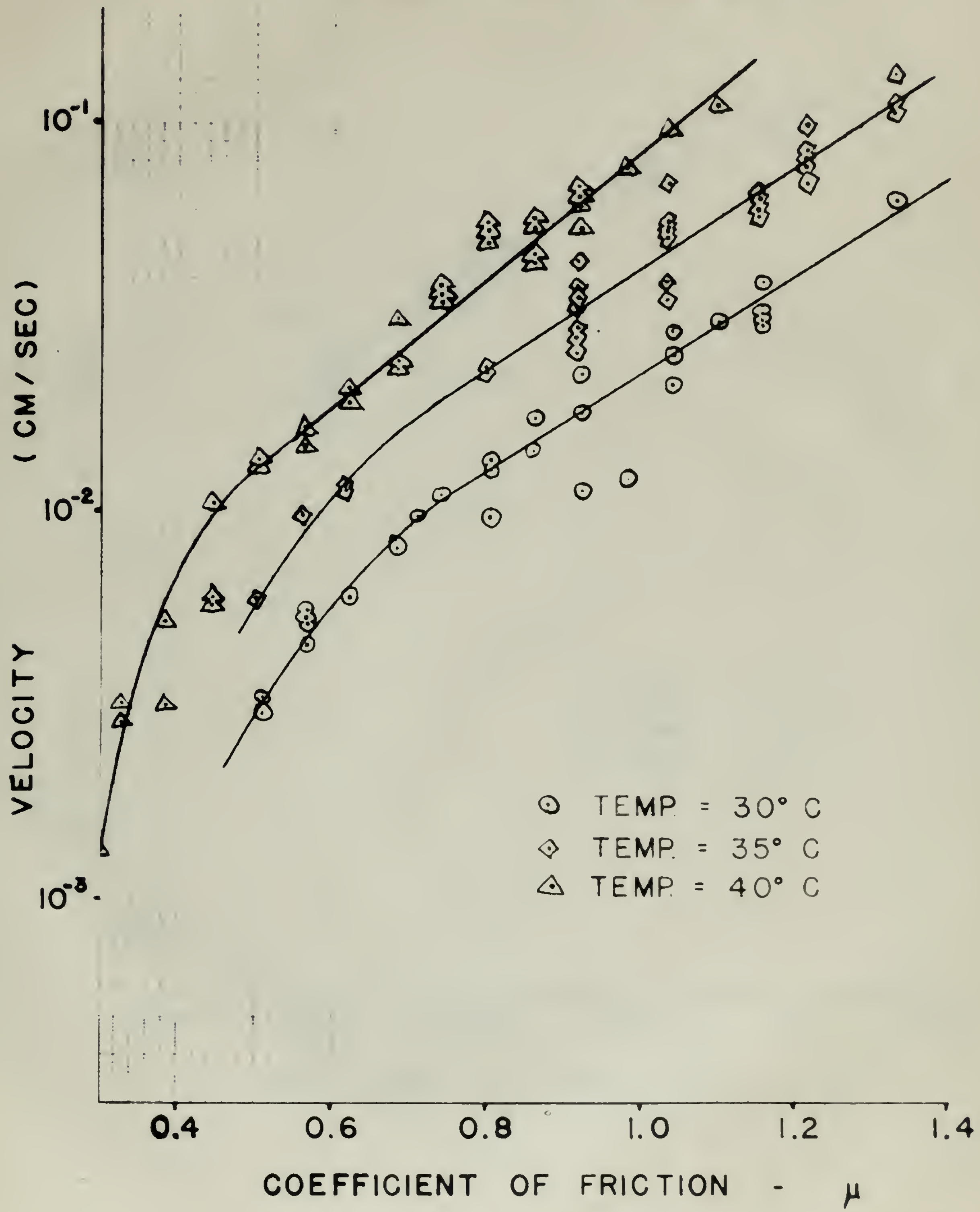

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FIGURE IV

PLOT OF LOG VELOCITY AGAINST COEFFICIENT OF FRICTION AT CONSTANT TEMPERATURE

NEOPRENE ON ROUGHENED GLASS

NORMAL LOAD = 365 GM

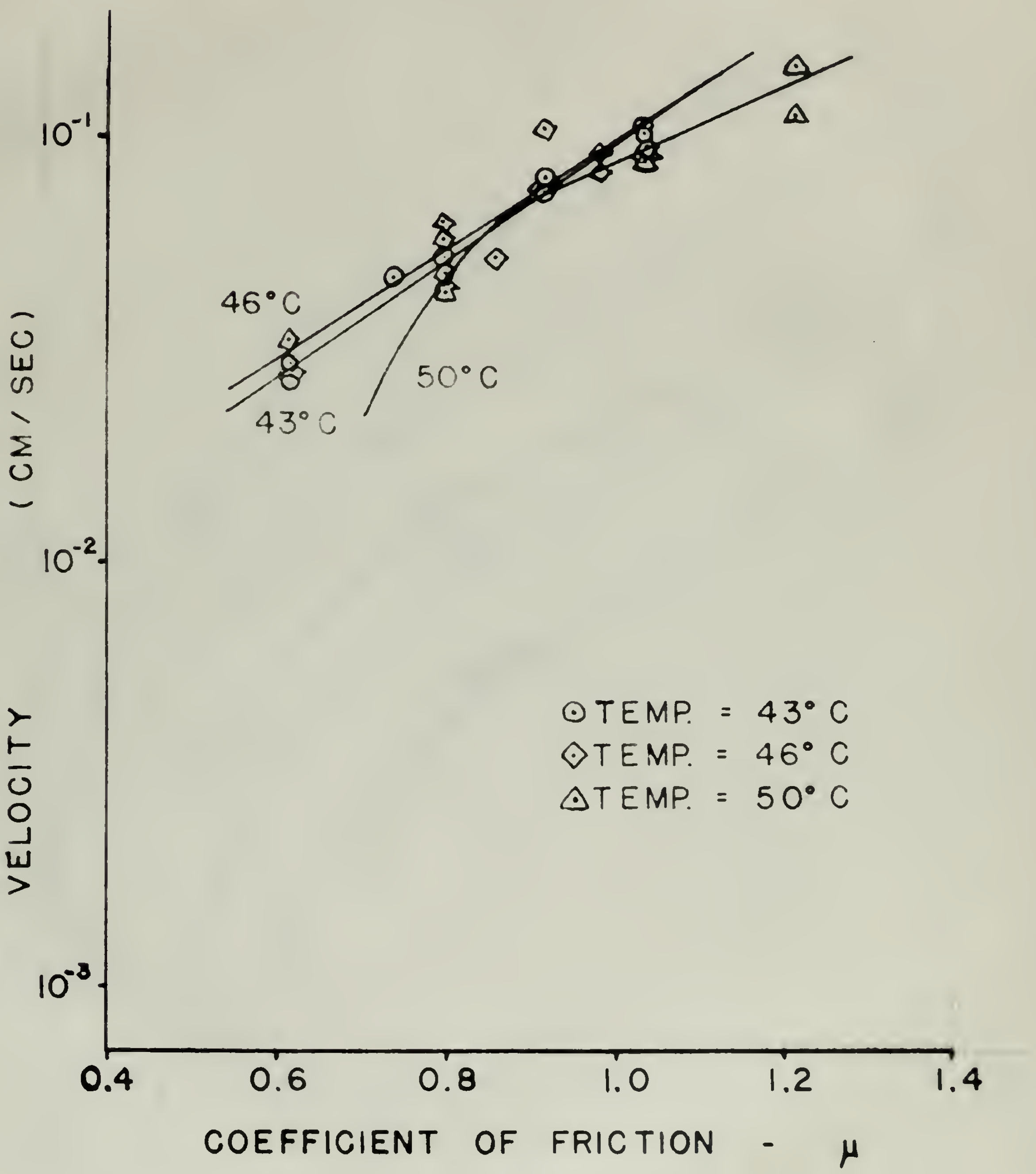
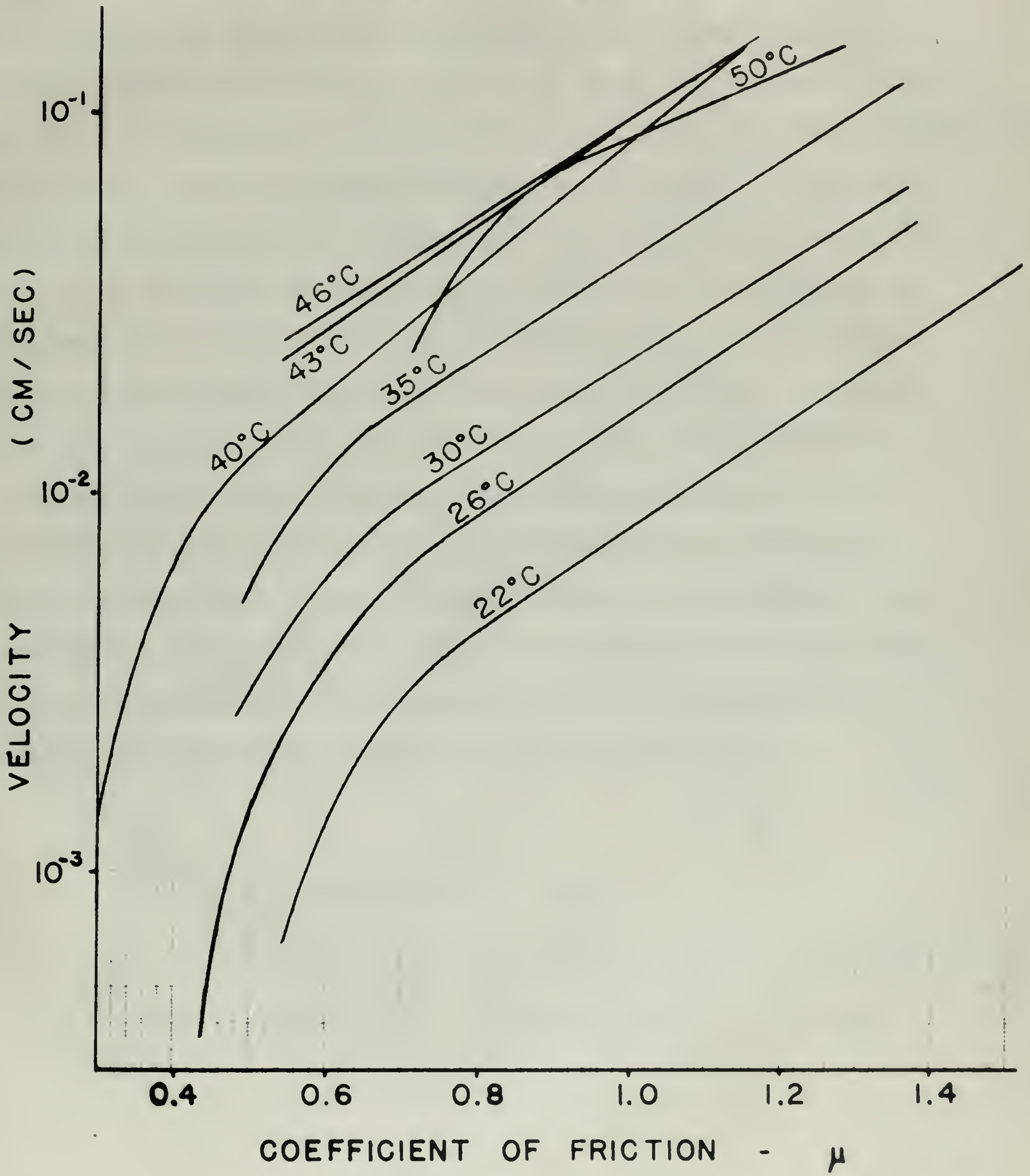


FIGURE V

PLOT OF LOG VELOCITY AGAINST COEFFICIENT OF FRICTION AT CONSTANT TEMPERATURE

COMPOSITE PLOT OF DATA

NEOPRENE ON ROUGHENED GLASS
NORMAL LOAD = 365 GM



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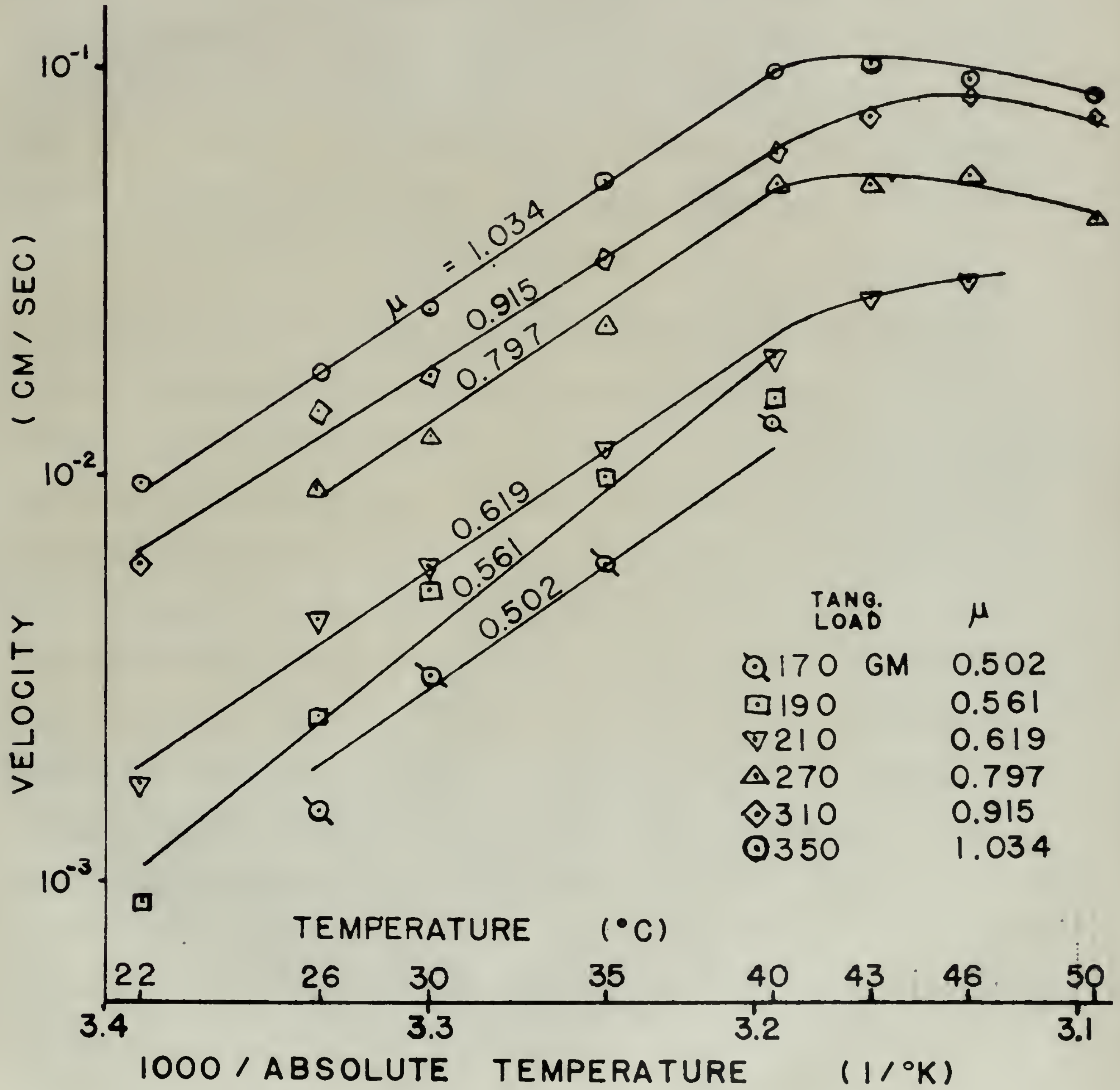
to fill the environment around the disk. The amount of moisture in the air has a definite effect on the performance of the disk; as the moisture is increased, the disk slows down, sometimes even stopping. With the reintroduction of dry air, the disk will resume its rotation.

From the data obtained, it was possible to make a cross-plot—a plot of the logarithm of velocity against the temperature. For reasons we shall see later, the temperature scale was plotted as the reciprocal of the absolute temperature. These data are seen in Figure VI. Each point on this plot represents the average of all observations at that temperature and tangential load. It is clear that the points for constant μ, up to a temperature of 40°C, can be connected satisfactorily by a straight line, so, the straight lines were passed through the points by mathematical analysis. The curves above 40°C became more horizontal, and in some cases, the data indicated a downward trend. However, because of the doubtful nature of the data over 40°C, the curves above this can only be considered to be estimates. It is to be noted that only one thin film of neoprene was used in all this investigation. There has been no evidence of deterioration or aging of the film, no matter what the condition of operation, and there has been no observable deposit of neoprene on the roughened glass surface.

FIGURE VI

PLOT OF LOG VELOCITY AGAINST THE RECIPROCAL OF THE ABSOLUTE TEMPERATURE FOR CONSTANT COEFFICIENT OF FRICTION

NEOPRENE ON ROUGHENED GLASS
NORMAL LOAD = 365 GM



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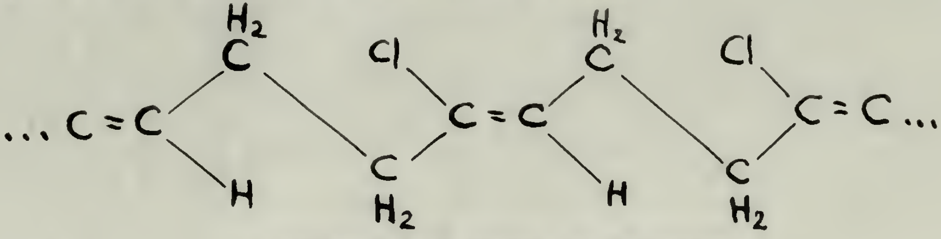
DISCUSSION OF RESULTS

From the results obtained (Figure V) we can see that there are two distinct regions to the curve of ln V vs. μ—for low values of μ the curve has a steep slope and is concave downward, while for higher values of μ the curve is linear. From a cross-plot of the data (Figure VI) we see that within the temperature range of 22°C to 40°C the relation of ln V to temperature is linear. Above this range the curve becomes more horizontal, and the linearity no longer holds. With these relationships in mind we propose an explanation of the sliding process.

We must first know, however, something of the material itself. The physical properties of neoprene (polychloroprene) are very similar to those of rubber, but it is more resistant to hydrocarbon oils and less subject to high-temperature deterioration. Structurally, it consists of a network of long-chain molecules coiled upon themselves. The bonds at the molecule junctions may be primary cross links of the network or secondary bonds between the chain elements. When the neoprene is subjected to local stresses the molecules are uncoiled, and this process of uncoiling accounts for the elastic deformation of the substance. When the stresses are relieved, the molecules return to a coiled state, the position of which depends on the strength of the primary and secondary bonds.



Chemical Structure of Neoprene

Both the glass and neoprene surfaces are, microscopically, very irregular. When they are placed together, the contact is not universal over the entire surface but is made only at isolated points which we shall call "islands of contact." In the words of Bowden [5], contact between the two surfaces can be likened to inverting Switzerland on Austria. As the neoprene film moves over the glass surface, the islands tend to remain stationary—in contact with the glass—while the surrounding non-contacting area moves with the bulk of the neoprene. This causes an elastic shear stress to be set up in the neoprene in the area around each island. When the shear stress reaches a particular value, τ_0, the island slides back along the glass, and the neoprene in the vicinity of that island returns to an unstressed position. Referring to the data in Figure VI we see that the velocity is dependent on the temperature of the environment of the contacting surfaces; so, we can say that the shear stress necessary to cause the slip of an island is made up of two components—one due to the applied tangential load and the other due to the thermal vibration of the material. With no tangential load the molecules of both substances are in vibration due to the temperature of the surroundings, but without a preferred direction and without an amplitude of vibration sufficient to break the contact. However, when a tangential load is applied, the vibrations are influenced to act toward relieving the stress induced by the applied load, and the shear stress in each island can reach a value high enough to cause local slip. The sum of all the randomly occurring local slips over the contacting surface results in the steady relative motion of the two surfaces.

The shear stress caused by the thermal vibration of the material is the difference between the shear stress necessary to cause local slip (τ_0) and the local shear stress caused by the applied load (τ). The thermal vibration energy is one component of the elastic strain energy of the glass-neoprene bond in the islands of contact. If we assume the relationship between stress and strain to be linear over the range of τ to τ_0 we can write

$$A = \frac{(\tau_0 - \tau)^2 s l}{2G} \tag{3}$$

where

A : energy of thermal vibration

s : area of the island of contact

l : initial length of participating portion of the molecules

G : constant of proportionality between stress and strain (shear modulus)

From the Boltzmann-Einstein Theorem we can obtain an approximation for the steady relative motion between glass and neoprene.

$$V = C \exp\left[-\frac{A}{KT}\right] \tag{4}$$

where

V : sliding velocity

C : "frequency factor" and is approximately constant

K : Boltzmann's constant

T : absolute temperature

The frequency factor C can be thought of as being, in the first approximation, proportional to the frequency with which the atomic configuration of an island is changing, the number of islands in the contacting surfaces, and to the relative gross sliding displacement arising from the slip of one island.

Taking the logarithm of both sides of equation (4) and substituting equation (3) we then have

$$\ln V = \ln C - \frac{(\tau_0 - \tau)^2 sL}{2GkT} \tag{5}$$

When τ_0 and τ are of the same order of magnitude, the resultant curve of ln V vs τ is a parabola concave downward until $\tau = \tau_0$, when it is then constant at the value of ln C.

This is not the complete picture, though. Previous investigators [9] have shown that there are two bond strengths in rubber—and hence in neoprene—one of which is far stronger than the other. This implies two activation energies, one of which is very small. We then propose to say that the local shear stress τ is of the same order of magnitude as the weak bond strength (τ_{01}) and both are very much smaller than the strong bond strength (τ_{02}). Following the form of equation (3) we can then write

$$A = A_1 + A_2 \tag{6}$$

$$A_1 = \frac{(\tau_{01} - \tau)^2 s_1 L_1}{2G_1} \tag{7}$$

$$A_2 = \frac{\tau_{02}(\tau_{02} - 2\tau) s_2 L_2}{2G_2} \tag{8}$$

where the subscripts 1 refer to the weak bonds and 2 refer to the strong bonds.

With this in mind we substitute equations (7) and (8) into equation (4) and proceed to synthesize the curve of ln V vs τ. This construction can be seen in figure V-A. The expression for A_1 as a function of τ is a parabolic shape, while for A_2 it is linear in τ. Subtracting both of

these from ln C we get a resultant curve which is concave downward at the low values of τ, and which changes to a linear relation with a positive slope as τ increases. This is precisely the form the experimental data take in the first approximation. At low values of τ, A_1 and A_2 are of the same order of magnitude. Since $\tau_{01} \ll \tau_{02}$, and $\tau \ll \tau_{02}$ then

$$\frac{S_1 l_1}{G_1} \gg \frac{S_2 l_2}{G_2} \tag{9}$$

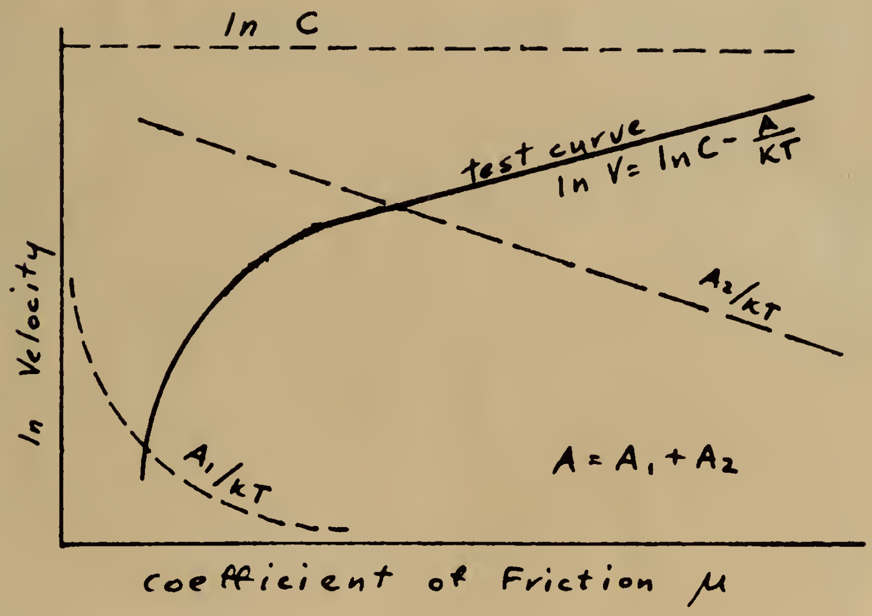


Figure V-A Synthesis of test Curve

If we consider only the strong bonds, i.e., the linear portion of the ln V vs F curve, we can write equation (5) as

$$\ln V = \ln C - \frac{(\tau_{02} - \tau)^2 S_2 l_2}{2 G_2 k T} \tag{10}$$

We shall assume the tangential force F to be equal to the product of the true area of contact s_t and the local shear stress τ so that we can predict the theoretical shape of the lnV vs F curve as being

$$\frac{\partial \ln V}{\partial F} = \frac{(\tau_{02} - \tau)\, s_2 \ell_2}{S_t G_2 K T} \tag{11}$$

We see that when τ is very much smaller than τ_{02} the slope is approximately constant. Previously, we have said that τ_{01} was very much smaller than τ_{02}, so the term involving τ_{01} can be neglected safely without interfering materially with the explanation of the slope.

From equation (10) we can calculate the theoretical slope of the cross-plot of the data (Figure VI). This becomes

$$\frac{\partial \ln V}{\partial (1/T)} = \frac{(\tau_{02} - \tau)^2 s_2 \ell_2}{2 G_2 K} \tag{12}$$

which is constant for a particular value of τ. This is what is expected, but there is no explanation for the behavior of the curves at temperatures above 40°C. It seems very possible that some reversible chemical change takes place in the structure of the neoprene.

By combining equations (11) and (12) we can find the ratio τ_0/τ as

$$1 + 2\left[\frac{-\partial \ln V/\partial(1/T)}{TF\,\partial \ln V/\partial F}\right] \approx \frac{\tau_0}{\tau} \tag{13}$$

From our data we have determined that this ratio is approximately 35.2

To find the thermal vibration energy which must be supplied to cause the islands to slip within the linear limits of the plots, we must combine

equations (3) and (12) which give

$$\frac{A}{kT} = \frac{\partial \ln V / \partial \left(\frac{1}{T}\right)}{T} \qquad (14)$$

from which we can solve for A. This was found to be 1.68 x 10^{-12} ergs/island, or, of the order of one electron volt per island.

The total energy which must be supplied by the applied tangential force and the thermal vibrations is the activation energy, E, and is given by

$$E = \frac{\tau_0^2 s l}{2G} \qquad (15)$$

We can estimate this if, in equation (3), we consider τ^2 to be negligibly small. We then have

$$A = \frac{\tau_0 (\tau_0 - 2\tau) s l}{2G} = E\left(1 - 2\frac{\tau}{\tau_0}\right) \qquad (16)$$

We have computed this to be 1.78 x 10^{-12} ergs/island. The work done by the applied tangential force per island is the difference of the quantities E and A.

In order to find the magnitude of τ we must know something of the true area of contact. From our supposition of the nature of the surfaces and of the contact, it is obvious that the true area of contact is less than the apparent area. From a paper by Denny [3] we are able to relate the ratio of the areas and the ratio of the apparent pressure to the elastic modulus of the substance at zero stress (p/E_0). From experimental data we have found this latter ratio to be about 2.08 x 10^{-3}. The work of Denny was carried out using gelatin, but it appears to be reasonable to assume that the experimental results for gelatin can be applied to neoprene.

We then get the ratio of true area to apparent area to be 0.0375, or a true contact area of 0.0402 cm^2 for our equipment. From this we have determined that τ is 7.36×10^6 dynes/cm^2. The shear stress necessary to cause slip is, from the ratio of τ_o to τ, 2.42×10^8 dynes /cm^2. We now know the force applied per island and the local shear stress. We have previously assumed that the force is proportional to the stress, and so we determine that the area per island is about 6.18×10^{-13} cm^2. The number of atoms per island is about 1235, and the energy per atom involved in causing slip becomes 2.72×10^{-15} ergs or 3.91×10^{-2} Kcal/mole. This is the bond strength per atom for islands in which all the atoms are participating in the bond. However, it is entirely possible that in an island only one atom may be responsible for the bond. In such a case the bond strength is about 48.2 Kcal/mole, which is of the order of known atomic bond strengths. (Oxygen-oxygen atom bond is 35 Kcal/mole; that of the carbon-carbon bond is 58.8 Kcal/mole.)

It is now possible to calculate the magnitude of the quantities $s_1 l_1/G_1$ and $s_2 l_2/G_2$ with the idea of eventually determining each factor. From the data on the linear portion of the curve we can arrive at a value for $s_2 l_2/G_2$. For the parabolic section it is necessary to separate the curve into its two components. We have used, for analysis, the interpolated curve of lnV vs μ at 28.2°C, and we have arbitrarily chosen a reference point at $\mu = 0.5$ from which to make measurements. Subtracting the value of ln V of the test curve from the value of ln V for the linear portion extended to this value of μ will give the value of A_1/kT. We have estimated that the curve departs from the linear at $\mu = 0.73$, which permits us to

determine τ_{01}. From μ and the true area of contact, τ at each point can be determined. With equation (7) we can then find the value of $s_1 l_1/G_1$, and we see that relation (9) does in fact apply; the factor between the two quantities being over 200.

A summary of our data is contained in Table I. Previously we have mentioned that Schallamach carried out a similar investigation but on a larger scale [8]. The data he obtained using (a) rubber on ground glass, and (b) rubber on silicon cloth are compared with our data. His data, in the first approximation, yielded linear results as did ours, and in spite of the difference in size of the equipment, the values of A and E come out in remarkably close agreement. The great difference between values of C for Schallamach's data can be explained--the fact that the cloth is rougher than the glass would indicate higher normal pressures at the contacting peaks and thus higher values of τ. High values of τ would increase the gross sliding displacement of a single peak, and A would be less for the same τ. But why our value of C is so much higher is not clear. It could be that in grinding the neoprene surface to match the glass more islands may be brought into contact. With more islands of contact τ would be reduced. This would be in keeping with the comparative values of τ_0/τ.

TABLE I

Comparison of Data in Linear Range

Source	M.I.T.	Schallamach	
Materials	Neoprene on Roughened Glass	Rubber on Ground Glass (a)	Rubber on Silicon Carbide Cloth (b)
Load W (gm)	365	6.44×10^3	6.44×10^3
Temperature Range (°C)	22° - 50°	20 - 40	20 - 40
Range of F (gm)	240 - 510	$8 \times 10^3 - 10 \times 10^3$	$8 \times 10^3 - 10 \times 10^3$
Range at $10^3 V$ (cm/sec)	3.23 - 150	0.1 - 5.0	25 - 1000
$\partial \ln V/\partial(\frac{1}{T})$ (°k)	-1.22×10^4 @ 282g	-1.29×10^4 (@ 9 kg)	-1.15×10^4 (@ 9 kg)
$\partial \ln V/\partial F$ (1/gm)	8.4×10^{-3} @ 28.2°C	1.38×10^{-3} @ 25°C	0.92×10^{-3} @ 20°C
τ_0/τ	35.2 @ 282 g; 28.2°C	9 (@ 9 kg; 25°C)	12 (@ 9 kg; 20°C)
A/kT	40.5 "	43 "	39 "
A ergs	1.683×10^{-12} "	1.763×10^{-12} "	1.573×10^{-12} "
E/kT	42.9 "	56 "	47 "
E ergs/island	1.785×10^{-12} "	2.32×10^{-12} "	1.95×10^{-12} "
C	121.4×10^{14}	5.0×10^{14}	32×10^{14}

CONCLUSIONS

From the influence of temperature on the sliding velocity of the neoprene film, it is suggested that the friction of rubber is an effect of thermal activation of the substance. The thermal activation is influenced by a mechanically applied load which serves to determine the direction of relative motion so as to relieve the local stresses formed. Furthermore, it is suggested that in the contact of neoprene and glass there are two distinct strengths of bonds. The weak bonds are influenced primarily by the applied load, and the strong bonds are directed by the load but influenced mainly by the thermal activation.

Further work is indicated along the lines of extending the extremities of the curve of ln V vs μ, particularly in the region of high values of μ and extending the temperature range of the investigation, in particular to lower temperatures. It would also be of interest to be able to determine the values of s and G as would apply for the two bond strengths. Some investigation is indicated as to the behavior of neoprene at temperatures over 40°C to determine the nature of the change of the material at elevated temperatures. The apparatus is so arranged that other materials, such as plastics, may be substituted for the glass plate, and films of other rubber-like materials substituted for the neoprene. The friction test can be carried out in various gaseous atmospheres. This should eventually lead to an understanding of the effect on sliding friction of surface and operating conditions of any materials in contact.

FIGURE VII

Photograph of Test Apparatus Enclosed in Controlled Temperature Box, Ready for Operation.

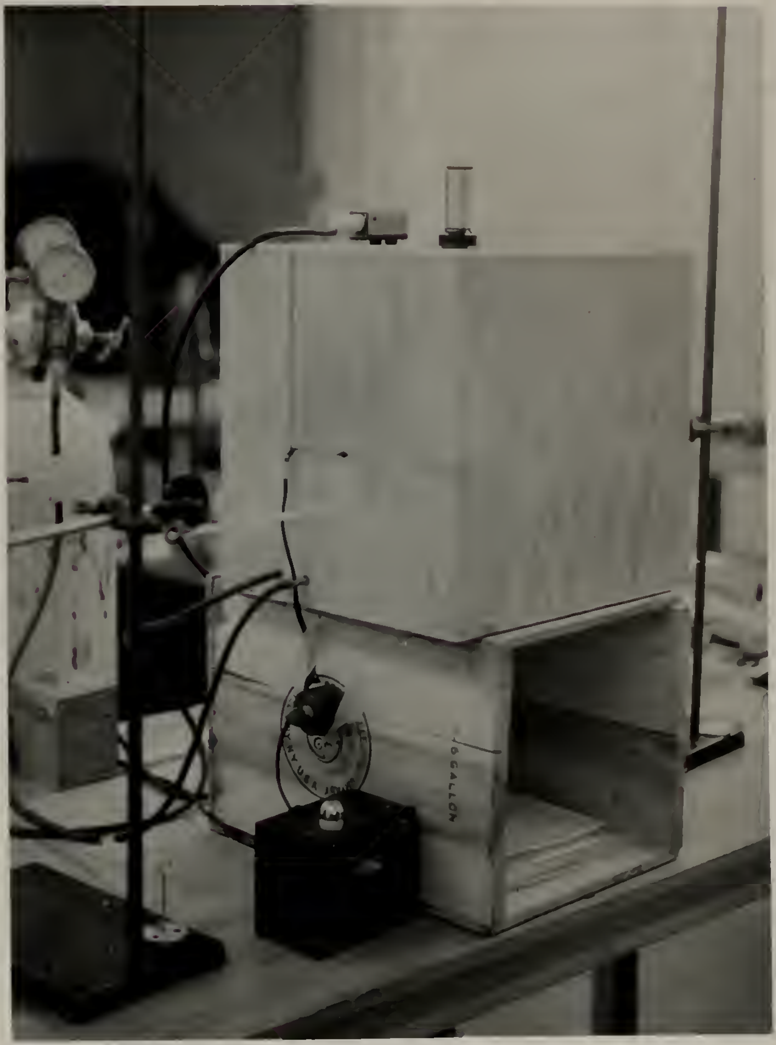


FIGURE VIII

Photograph of Test Apparatus in Controlled Temperature Box; Access Panel Removed.

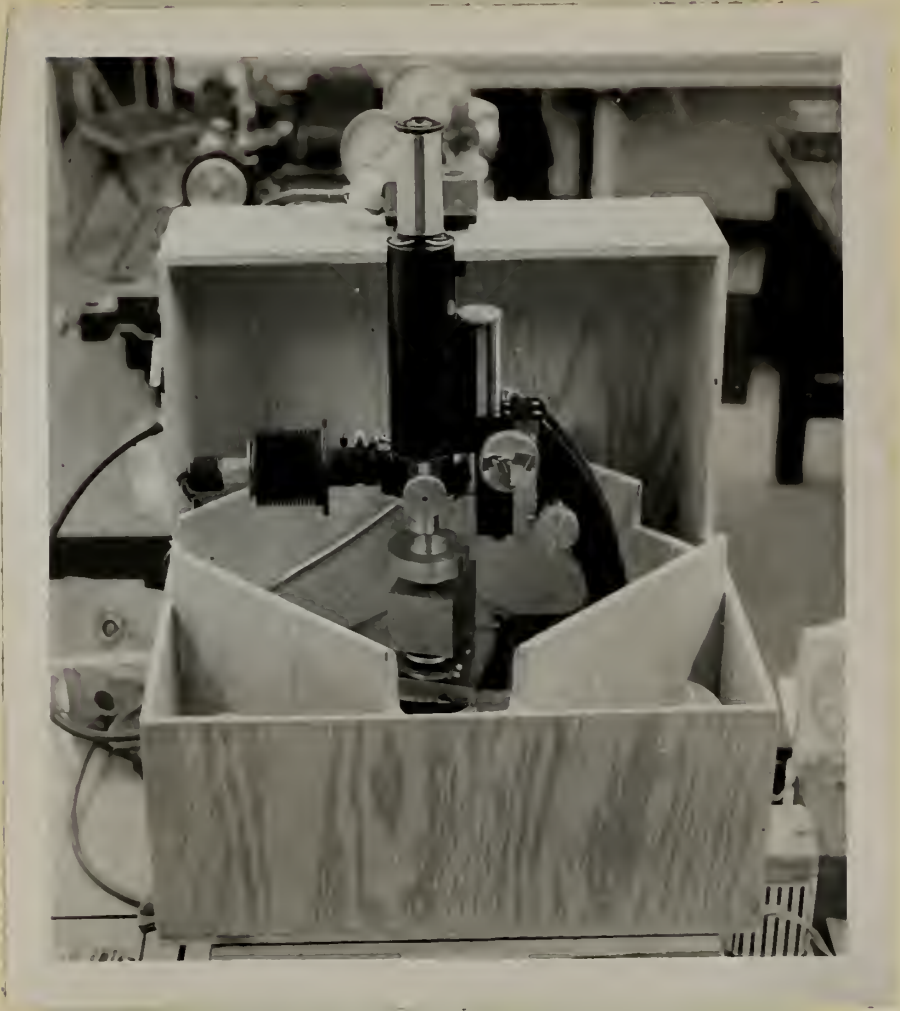


FIGURE IX

Photograph of Test Block

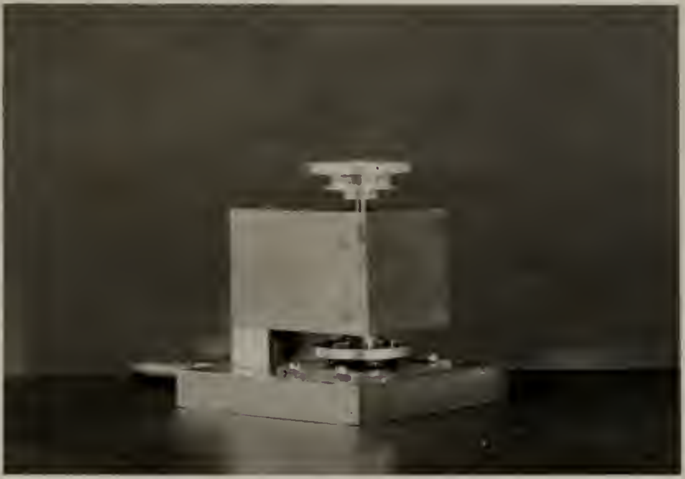
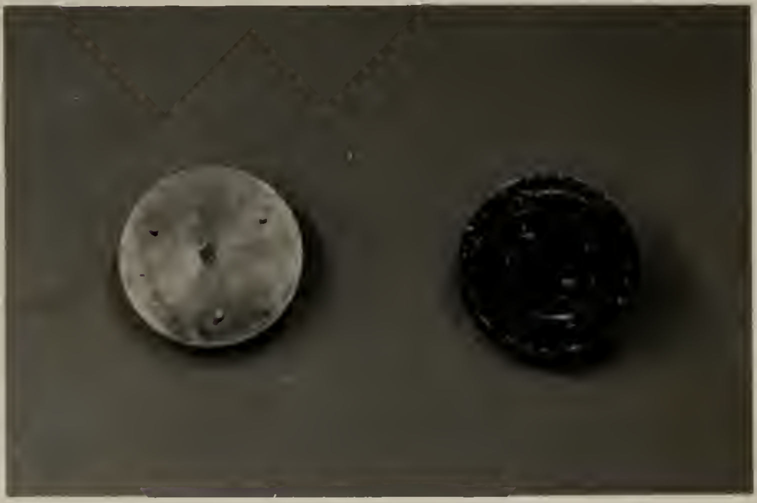


FIGURE X

Photograph of Disks Showing Top Side (Left) and Bottom, or Annulus, Side Coated with Neoprene.



APPENDIX

APPENDIX A

Definition of Symbols

A = Strain energy supplied by thermal vibration

a = Typical atomic area (5×10^{-16} cm^2)

C = Frequency factor, approximately constant

d = Typical atomic spacing (2.4×10^{-8}cm)

E = Activation energy

E_o = Elastic modulus at zero stress

F = Applied tangential load [gms]

G = Proportionality constant between stress and strain; analagous to the usual shear modulus

k = Boltzmann's constant (1.38×10^{-16} ergs/°K)

l = Initial length of participating portions of molecules

p = Apparent pressure

s = Area of island of contact

s_a = Apparent area of contact

s_t = True area of contact

t = Temperature [°C]

T = Absolute temperature = $t + 273.2$ [°K]

V = Steady velocity of sliding [cm/sec]

W = Normal load [gms]

μ = Coefficient of friction

τ = Local shear stress

τ_o = Shear stress necessary to cause local slip

APPENDIX B

Summary of Data

SUMMARY OF DATA

VELOCITY AS A FUNCTION OF TANGENTIAL LOAD AND TEMPERATURE

(Body of Table is velocity in cm/sec x 100)

Tang. Load	Coeff. Frict.	Temperature (°C)							
gms.	μ	22°	26°	30°	35°	40°	43°	46°	50°
100	0.295					0.136			
110	0.325					0.29 0.328			
130	0.383		0.0102			0.326 0.525			
150	0.442		0.0408 0.052 0.093			0.59 0.60 1.06			
170	0.502		0.15	0.31 0.337	0.61	1.37 1.38			
190	0.561	0.089	0.235 0.25 0.29	0.46 0.521 0.54 0.57	1.0	1.48 1.66			
210	0.619	0.175	0.402 0.46 0.47	0.605	1.17 1.18	1.91 1.91 2.1	2.65 2.94	2.87 3.34	0.13
230	0.68	0.257		0.817		2.36 2.42 3.25			
240	0.707			0.99					
250	0.737	0.323 0.48	0.619	1.13		3.6 3.67 3.88	4.7		
270	0.797		0.785 0.83 1.05	0.987 1.33 1.40	2.33 2.35	5.0 5.38 5.47	5.25	4.78 5.74 6.28	4.3 4.5

Tang. Load	Coeff. Frict.	Temperature (°C)							
gms.	μ	22°	26°	30°	35°	40°	43°	46°	50°
280	0.827	0.505 0.521							
290	0.856	0.494 0.567		1.47 1.79		4.52 4.55 5.6 5.75		5.2	
310	0.915	0.511 0.603 0.627 0.67	1.33 1.53	1.15 1.83 2.31	2.61 2.81 3.07 3.46 3.67 3.9 4.6	5.5 6.47 6.6 7.0	7.5 8.15	7.86 7.86 10.6	7.5 7.8 8.1
330	0.975	0.796		1.22		7.96		8.35 [illegible].3	
350	1.034	0.94 0.956	1.72 1.85	2.16 2.61 3.0	3.63 4.05 5.36 5.6 5.7 5.8 7.3	10.0	10.3 10.5	9.57	8.9 8.9
370	1.092	1.135 1.368		3.18		11.6			
390	1.15	1.345		3.10 3.20 3.31 4.03	6.11 6.2 6.67 6.81				
410	1.21		2.6 3.15 3.26 3.45 3.72		7.4 8.1 8.3 8.8 10.3				11.4 15.0
420	1.239	1.68 1.704							
450	1.329		4.52 4.7	6.6	11.2 11.8 15.0				
470	1.388	2.42							
510	1.505	4.25							

APPENDIX C

Details of Construction of Test Apparatus

FIGURE XI

ASSEMBLED VIEW OF TEST APPARATUS
(FULL SCALE)

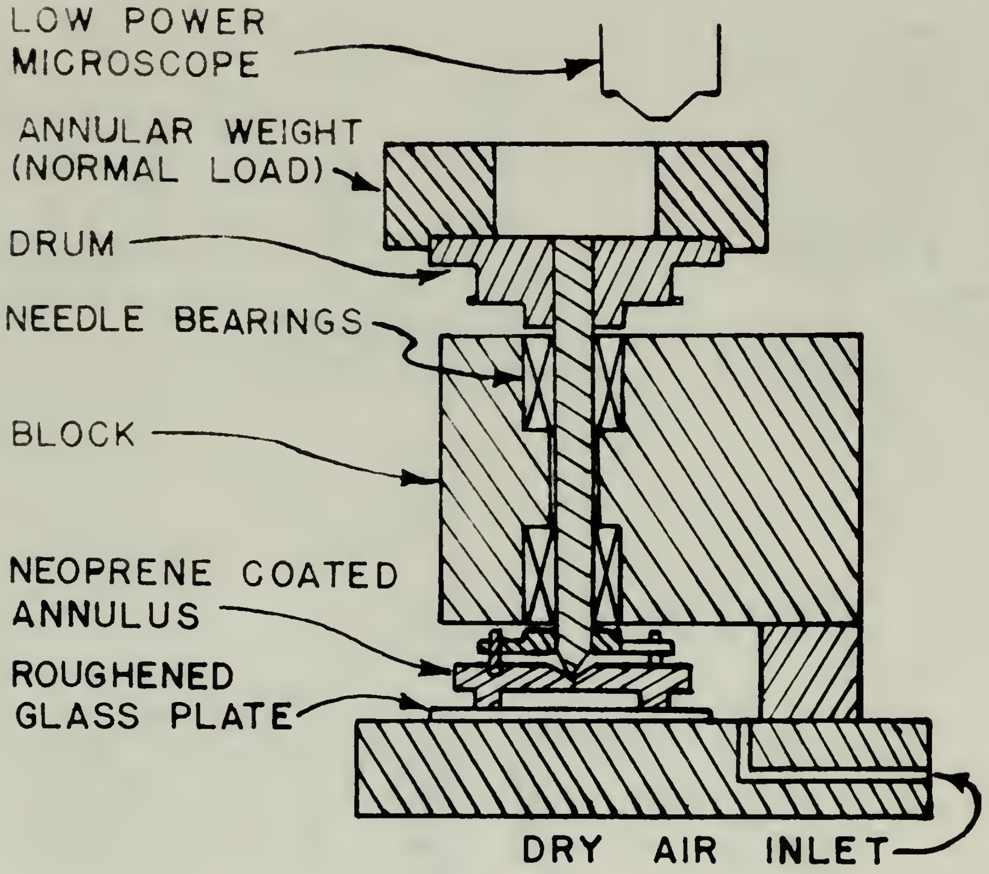


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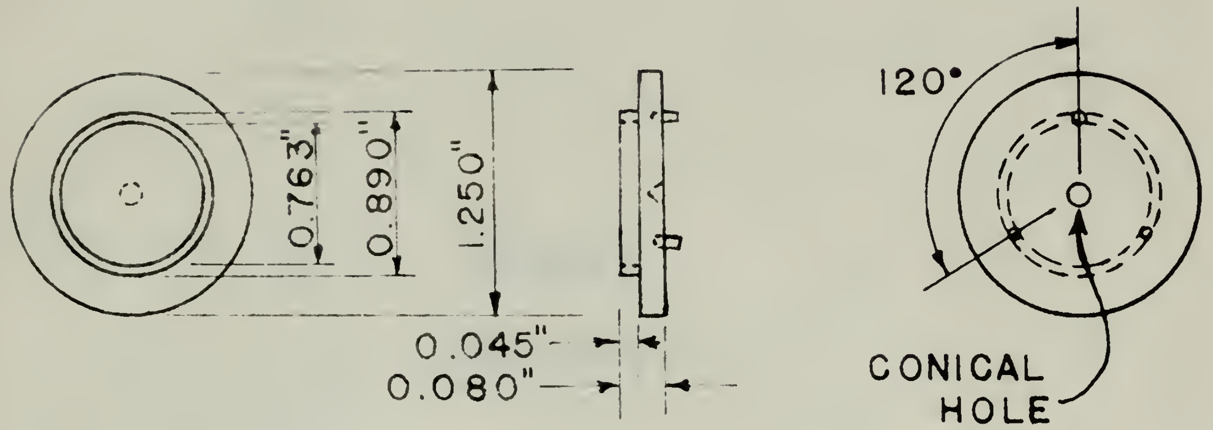
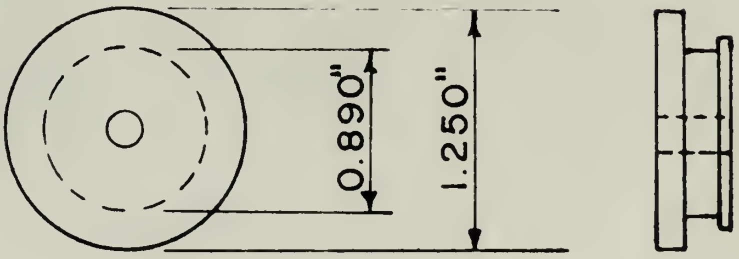
FIGURE XII

DETAILS OF DISK AND DRUM
(FULL SCALE)

DISK



DRUM



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APPENDIX D

Computations

Substituting the values obtained:-

$$\frac{\tau_0 - \tau}{2\tau} = 17.1$$

$$\frac{\tau_0}{\tau} = 1 + 2\left(\frac{\tau_0 - \tau}{2\tau}\right) = 1 + 2(17.1) = 35.2$$

$$\frac{\partial \ln V}{T\,\partial(1/T)} = -\frac{(\tau_0 - \tau)^2 s l}{2G K T} = \frac{A}{KT} = 40.5 \qquad (K = 1.38 \times 10^{-16}\ \text{ergs}/{}^\circ K)$$

from which $A = 1.683 \times 10^{-12}$ ergs $\quad$ (1 e.v. $= 1.6 \times 10^{-12}$ ergs)

or $\quad A = 1.05$ e.v.

$$A = \frac{\tau_0^2 (1 - 2\frac{\tau}{\tau_0}) s l}{2G} = E\left(1 - 2\frac{\tau}{\tau_0}\right) \qquad \text{when } \tau << \tau_0 \qquad (16)$$

from which $E = 1.785 \times 10^{-12}$ ergs/island.

At the assumed point:- $\ln V = -3.465$

$$\ln V = \ln C - \frac{A}{KT}$$

or $\quad \ln C = \ln V + \frac{A}{KT} = -3.465 + 40.5 = 37.035$

and $\quad C = 1.214 \times 10^{16}$

F applied per island: $\frac{E - A}{d} = \frac{(1.185 - 1.683) \times 10^{-12}}{2.4 \times 10^{-8}} \left[\frac{\text{erg}}{\text{cm}}\right]$

$= 4.25 \times 10^{-6}$ dynes

From previous experimentation:-

$$\frac{p}{E_0}\ (\text{neoprene}) = \frac{0.365\ \text{Kg/cm}^2}{175\ \text{Kg/cm}^2} = 2.08 \times 10^{-3}$$

From Denny "Friction of Rubber-Like Materials" [3]

$$\frac{S_{true}}{S_{apparent}} = \frac{\partial}{W}(\text{gelatin})\ E_0(\text{gelatin})\ \frac{p}{E_0}$$

$$= 90 \times 0.2 \times (2.08 \times 10^{-3})$$

$$= 0.0375$$

or:- $S_t = 0.0402$ cm² for $S_{app} = 1.07$ cm²

Now $\tau = \frac{F}{S_t} = \frac{282}{0.0402} = 7.02 \times 10^3$ gm/cm²

or $\quad \tau = 6.88 \times 10^6$ dynes/cm²

$$\tau_0 = \tau\left(\frac{\tau_0}{\tau}\right) = (6.88 \times 10^6)(35.2) = 2.42 \times 10^8\ \text{dynes/cm}^2$$

Area per island $= s = \dfrac{F(\text{per island})}{\gamma} = \dfrac{4.25 \times 10^{-6}}{6.88 \times 10^{6}}$

$s = 6.18 \times 10^{-13}\ \text{cm}^2$

Number of atoms per island $= \dfrac{S}{a} = \dfrac{6.18 \times 10^{-13}}{5 \times 10^{-16}} = 1235$

where $a = 5 \times 10^{-16}\ \text{cm}^2$; typical area of atom.

Energy per atom $= \gamma_0 \times a \times \text{dist} = J_0 \times$ atomic volume

$= (2.42 \times 10^{8})(5 \times 10^{-16})^{3/2}$

$= 2.72 \times 10^{-15}$ ergs/atom

$= [(2.389 \times 10^{-11})(6.02 \times 10^{23})][2.72 \times 10^{-15}]$

$= 3.91 \times 10^{-2}$ Kgm Cal/mole for islands of 1235 atoms forming bond.

$= 48.2$ Kgm Cal/mole for islands of one atom forming bond.

Referring to Figure V-A:-

$$A = A_1 + A_2 \qquad (6)$$

For the linear portion of the curve:-

$\gamma = 6.88 \times 10^{6}$ dynes/cm^2 ; $\gamma_{02} = 2.42 \times 10^{8}$ dynes/cm^2

$$A_2 = \frac{\gamma_{02}(\gamma_{02} - 2\gamma) S_2 l_2}{2 G_2} = 1.683 \times 10^{-12}\ \text{dyne-cm} \qquad (8)$$

or:- $\dfrac{S_2 l_2}{G_2} = \dfrac{2 A_2}{\gamma_{02}(\gamma_{02} - 2\gamma)} = \dfrac{2(1.683 \times 10^{-12})}{[2.42 \times 10^{8}][2.28 \times 10^{8}]}$

$$\frac{S_2 l_2}{G_2} = 6.1 \times 10^{-29}\ \text{dyne}^{-1}\ \text{cm}^5$$

For the parabolic section:- (from the plot)

$$\frac{A_1}{KT} = (\ln V)_{\text{linear extended}} - (\ln V)_{\text{test curve}}$$

at $\mu = 0.5$:-

$$\frac{A_1}{KT} = \ln(4.35 \times 10^{-3}) - \ln(2.22 \times 10^{-3}) = 1.4702 - 0.7975$$

$= 0.6727$

From the curve estimate the linearity becomes predominate at $\mu = 0.73$.

at $\mu = 0.73$, $F = 266$ gm; $\gamma = 6.62 \times 10^6$ dynes/cm^2

$\mu = 0.50$; $F = 182$ gm; $\gamma = 4.54 \times 10^6$ dynes/cm^2

at $\mu = 0.73$; $\gamma_{01} - \gamma = 0$; or $\gamma_{01} = \gamma = 6.62 \times 10^6$ dynes/cm^2

$$\frac{A_1}{kT} = \frac{(\gamma_{01} - \gamma)^2 S_1 l_1}{2G_1} \qquad (7)$$

or. $$\frac{S_1 l_1}{G_1} = 2\left(\frac{A_1}{kT}\right)\frac{kT}{(\gamma_{01} - \gamma)^2} = \frac{2(0.6727)(1.38 \times 10^{-16})(301.4)}{(2.08)^2\, 10^{12}}$$

$$\frac{S_1 l_1}{G_1} = 1293 \times 10^{-29} \text{ dyne}^{-1} \text{ cm}^5$$

So $\frac{S_1 l_1}{G_1} >> \frac{S_2 l_2}{G_2}$ (by a factor of 212) (9)

$$\frac{\gamma_{02}}{\gamma_{01}} = \frac{242 \times 10^6}{6.62 \times 10^6} = 36.6$$

$$\frac{A_2}{A_1} = 60.2$$

APPENDIX E

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APPENDIX E

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